VLC Wireless Data Transmission of High Luminance LED Irradiated by a High Dose-rate Gamma-Ray

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Abstract

A visible light communication (VLC), a wireless data transmission method using light that is visible to the human eye, has a major advantage that it causes no EMI (electro-magnetic interference) to RFI (radio-frequency interference) susceptible SSC (systems, structures, and components) inside a reactor containment building of the nuclear power plant. A major problem which arises in the application of a VLC wireless data link in the reactor containment building is the presence of high dose-rate gamma irradiation fields. Gamma ray radiation constraints for the DBA (design basis accident) qualification of the RTD transmitter installed in the area of the RCS pump are typically on the order of 4 kGy/h with total doses up to 10 kGy. To test the feasibility of the VLC wireless data transmission method in the harsh environments of reactor containment building, high-luminance LEDs and photo detectors—key components of a VLC wireless system—were gamma-irradiated at a dose rate of 4 kGy/h for 72 h up to a total dose of 288 kGy. The radiation induced coloration in the bulbs of LEDs and photo detectors were observed. The wireless data transmission performance using the gamma ray irradiated devices has been explained. According to the experimental results, the transmission distance of high luminance LEDs whose bulbs were colored due to the high dose gamma ray irradiation increased compared to the LEDs before gamma ray irradiation.

Keywords

Visible Light Communication; Gamma Ray; RCB (Reactor Containment Building); Dose-rate; Irradiation; LED; RS-232C; Wireless, Data Transmission; Photo Detector

Introduction

The use of wireless communication is restricted in environments affected by electromagnetic waves; examples of such environments are the insides of hospitals, space crafts, and nuclear reactor buildings. Currently, sensor systems for monitoring and controlling safety system equipment and facilities are constructed using cables (actual wiring). Feasibility studies are aimed at establishing such systems using wireless technology. Despite the rapid development of wireless communication technologies, wireless sensor & communication network systems are not applied to nuclear power plants. For wireless communication to be applied to the inside of nuclear reactor buildings, the electromagnetic waves of wireless terminals should not cause malfunctions in nuclear power plant safety system equipment and facilities in nuclear reactor buildings. Additionally, verification technologies & systems should be established for wireless communication systems with weak electric field intensity to the extent that they do not cause malfunctions while sustaining the ability to guarantee highly reliable communication. The establishment of verification technologies & systems for the safety and high reliability of wireless communication and the development of standards and guidelines specifying the verification technologies and systems takes time. Therefore, wireless communication technologies are expected to be applied to fourth generation nuclear power plants, such as GEN IV, which is expected to be built in 20 to 30 years in the future. In the present study, visible light communication is reviewed for sensor/communication network systems in nuclear reactor buildings. VLC is a wireless communication technology that uses light visible to the naked eye. Using high-speed response and modulation properties, this technology sends information through the LED modulated light, and detects the modulated light using photo diodes or CMOS image sensors to restore the information. Visible light free from being subject to regulations on electromagnetic waves does not cause electromagnetic wave interference in safety system equipment and facilities in nuclear reactor buildings. Therefore, it is not necessary to satisfy the MIL-STD-461C/MIL-STD-462 requirements, the standards applied to nuclear power plant equipment and facilities. As its wavelength is much shorter compared

to radio waves, line-of-sight (LOS) communication is possible. VLC LED communication elements can be used to transmit broadband information as they can be driven by ultra-high speed modulation signals because they are made of GaAs(P) series III-V group semiconductors. As the transmission medium is visible light, which can be identified by the naked eye, their transmission lines can be easily established/ identified through the configuration of concentrating optical systems for transmission/receiving. For VLC spatial optical communication systems to be applied to sensor/ communication network systems in nuclear reactor buildings, the survivability of elements in VLC communication should be guaranteed in environments where the elements are exposed to high dose gamma rays, corresponding to the design basis accident (DBA) requirements. In this study, high luminance LEDs corresponding to the transmission units of VLC communication systems are irradiated with gamma rays at a dose rate of 4 kGy/h, corresponding to the DBA requirements, for 72 hours. Major components of safety system equipment installed in the nuclear reactor buildings should satisfy the quality assurance requirements for Class 1E equipment under IEEE 323-2003. Considering the operation requirement for 10 years, defined under these quality assurance requirements, an experiment to irradiate at least 288 kGy of gamma rays on the basis of the total irradiation dose (TID) has been conducted. Browning effects were found on high luminance LED bulbs. A transmission unit of a VLC communication system was configured using high luminance LEDs exposed to high dose gamma rays to conduct an experiment to transmit 115.2 kbps of RS-232C data, and the results are described below. The communication distances of the high luminance LEDs before and after gamma ray irradiation were compared and analysed.

High Dose Gamma Ray Irradiation Experiment

The gamma irradiation experiment was conducted online/offline using a 1-square-meter sized Co-60 high dose gamma ray source. During the online irradiation, the luminous intensity of high luminance power LEDs resulting from the irradiation of high dose gamma rays was measured online, as shown in Figure 1. Then, the rays were irradiated offline on high luminance LED elements in accordance with the quality assurance requirements (DBA, TID) for Class 1E equipment. In the offline assessment, changes in the luminous intensity in relation to the threshold voltage and driving current of high luminance LED elements were measured.

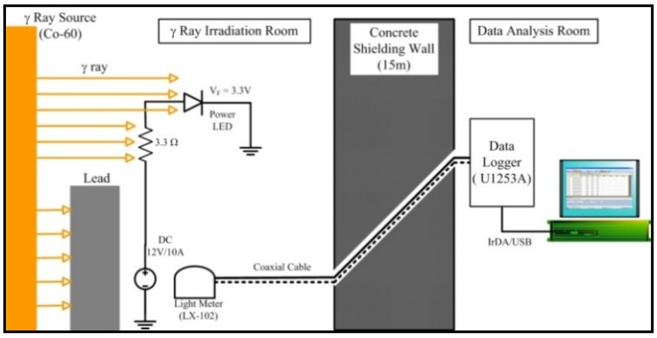

FIG. 1 EXPERIMENTAL SET-UP FOR ON-LINE MEASUREMENT OF THE LUMINANCE OF A PURE WHITE POWER LED (W724C0) DURING THE PERIOD OF A HIGH DOSE-RATE GAMMA-RAY IRRADIATION

Gamma rays were irradiated for two hours at a dose rate of 4 kGy/h for online assessment and for 72 hours at a dose rate of 4 kGy/h for offline assessment. Fig. 2 represents the luminance of a pure white power LED during the period of a high dose rate gamma ray (4 kGy/h) irradiation. And the range between the LED specimen and the LX-102 (lux meter) is about 500 mm. As shown in Fig.2, the luminance of the power LED falls off gradually 2.0% over 2000 seconds (30 min.). During the time span of 30 and 100 minutes, the lighting intensity of the one decreases more steeply. And after 100 minutes, the luminance of a sample (power LED) rises steadily again. After the gamma ray irradiation test (2 hours duration, 8 kGy TID) of the power LED was finished, a radiation induced color-center was not observed in the surface of the housing material of the LED specimen. The housing material of the power LED (W724C0) is made of silicon resin, which is radiation resistant material. And the electro-optical characteristics of the specimen (power LED) were not deteriorated greatly.

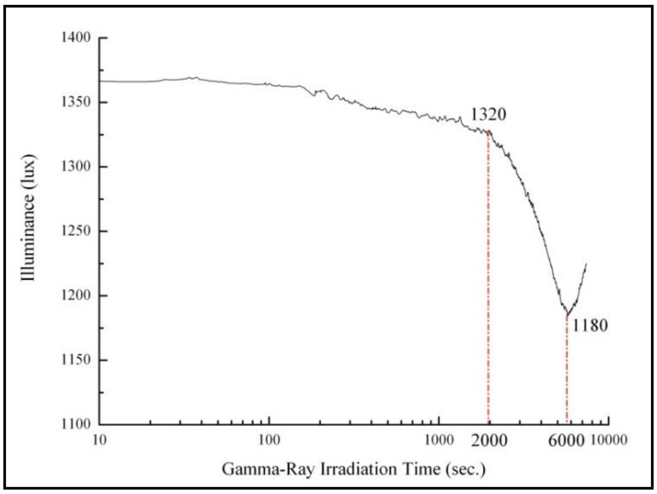

FIG. 2 ILLUMINANCE OF A PURE WHITE POWER LED DURING HIGH DOSE-RATE GAMMA-RAY IRRADUATION

High luminance power LEDs were attached with heat insulating boards and fans to constantly maintain the

high driving current (max. 1.4A) and junction temperature Tj on the p/n junction. Figure 3 and 4 show the bulb appearance of high luminance LEDs after irradiation of 288 kGy of gamma rays on the basis of the accumulated dose. The left figure shows a view of the high luminance LED bulb before irradiation, and the right figure shows a view of it after irradiation of 288 kGy of gamma rays. The color of the plastic or acrylic LED bulb became brown. The threshold voltage of the 5-mm and 3-mm diameter high luminance LEDs was measured, and according to the results, the values obtained before and after gamma ray irradiation were equal. Figure 5 shows the gamma irradiation characteristics of the high luminance power LED. The bulb (housing) shown in Figure 5 is made of silica resin which has excellent thermal properties, and can endure the high temperatures generated inside during light emission. As it can be seen from Figure 5 that a coloring phenomenon was observed on the reflecting plate of the high luminance power LED. The coloring resulting from high dose gamma ray irradiation appearing on glass, plastic, and acrylic materials cannot be observed by naked eye on the silica resin bulb of the high luminance power LED. Figure 6 shows the bulb appearance of photo diode after irradiation of 288 kGy of gamma rays. When a threshold voltage of the photo detector was measured after gamma ray irradiation experiment, the threshold voltage of the diode was zero (0.7 V in the normal state).

It is estimated that a bi-directional VLC wireless data link in the RCB (reactor containment building) area is not feasible, because the photo detector is not survivable in a high dose-rate gamma ray irradiation fields. So, in this paper, it was thought that uni-directional data link (sensor to data processing unit) is possible if it is assumed that the photo detector module is far away from the high dose-rate gamma ray source (nuclear fission reaction material) in the RCB area.

FIG. 3 HIGH DOSE GAMMA RAY IRRADIATION FOR HIGH LUMINANCE WHITE LED (DIA. 5MM)

FIG. 4 HIGH LUMINANCE LED BULBS DARKENED BY HIGH DOSE-RATE (4 KGY/H) GAMMA RAY IRRADIATION (DIA. 3MM, LEFT: BEFORE, MIDDLE: AFTER 8 KGY TID, RIGHT: AFTER 288 KGY TID)

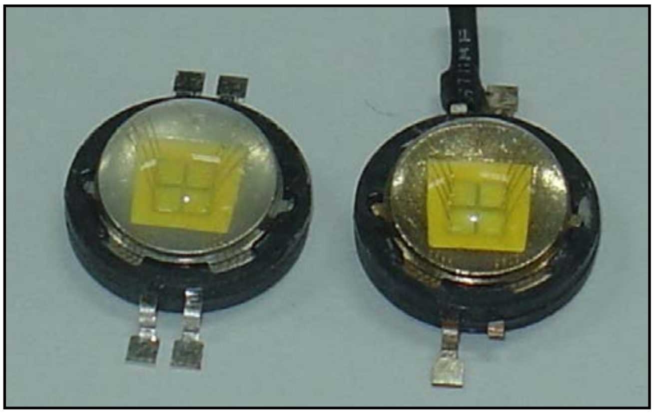

FIG. 5 POWER LED BULBS DARKENED BY HIGH DOSE-RATE (4 KGY/H) GAMMA RAY IRRADIATION (LEFT: BEFORE, RIGHT: AFTER 288 KGY TID)

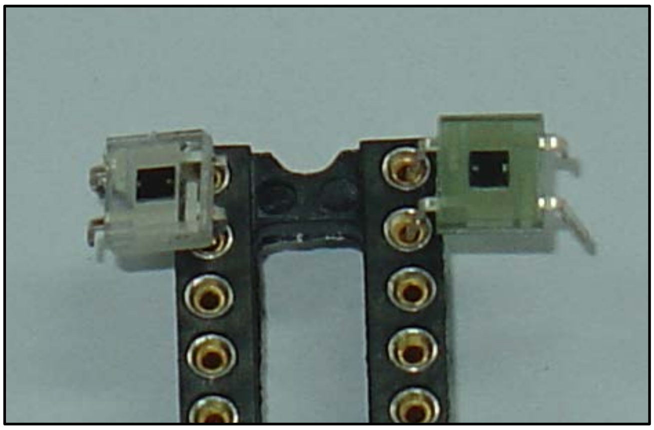

FIG. 6 PHOTO DETECTOR BULB DARKENED BY HIGH DOSE-RATE GAMMA RAY IRRADIATION (LEFT: BEFORE, RIGHT: AFTER 288 KGY TID)

Visible Light Wireless Data Transmission Experiment

An experimental setup was configured, as shown in Figure 7, for visible light wireless data transmission experiments. Arbitrary sine wave, as shown in Figure 8, was generated by the PC and transmitted to an LED driving circuit through an RS-232C interface. The LED

circuit modulated the RS-232C data transmitted by the PC into light and emitted the light to the space. The emitted light was then detected and amplified by a PD and measured using an oscilloscope. A linear guide was used to move the LED driving component and the PD detection module along the same axis. Transmission/receiving waveforms were compared using an oscilloscope to obtain the communication conditions for maximum distance. After obtaining the maximum possible communication distance, data were transmitted by the PC, and loopback data that went through the VLC transmission/receiving modules were received by the PC to measure transmission errors.

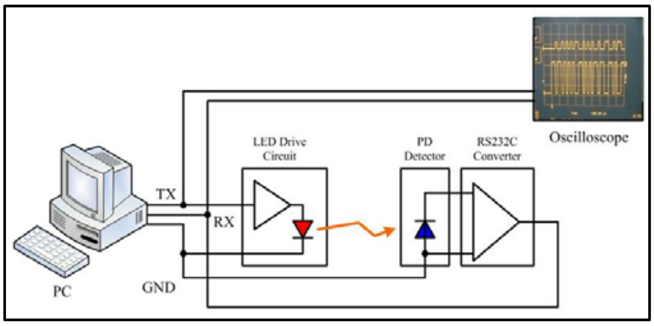

FIG. 7 EXPERIMENTAL SETUP FOR VLC WIRELESS DATA TRANSMISSION

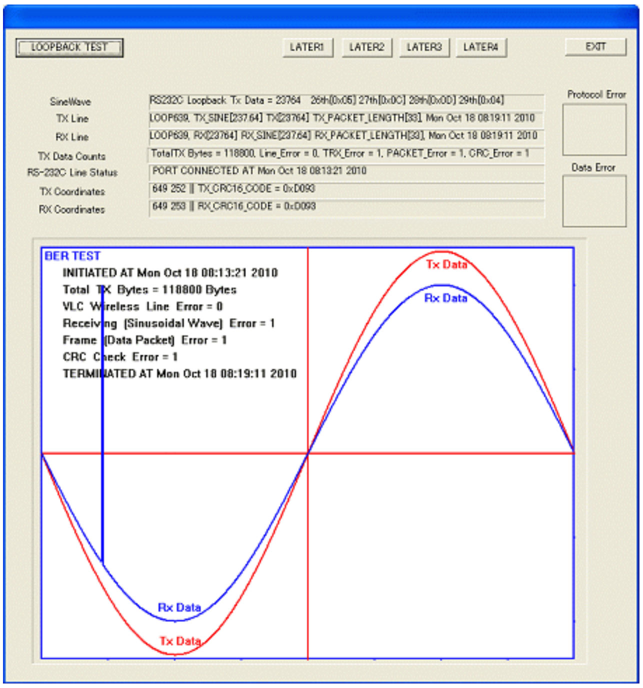

FIG. 8 ARBITRARY SINUSODIAL WAVE GENERATED BY THE PC (TOP: TRANSMITTED DATA, BOTTOM: RECEIVED DATA)

If data transmission error occurs, the peak is drawn in the receive waveform of the bottom side of Fig. 8 at the time of error occurrence. Therefore, we can easily discriminate the data transmission errors during the RS-232C loopback test. Figure 9 shows the TX and RX circuits for VLC data transmission. A photo IC (IS 486) was used as the PD element. The PD has higher sensitivity in the infrared region than in the visible light region. LED elements were replaced before and after gamma ray irradiation to measure wireless data transmission distances. The operating current of the LED element was set to be the maximum value.

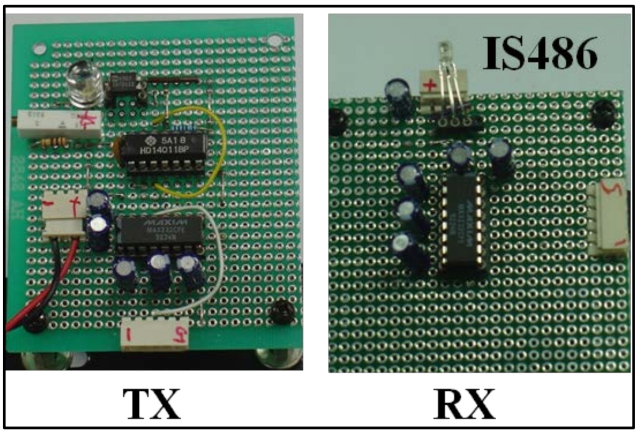

FIG. 9 TX AND RX CIRCUITS FOR RS-232C LOOPBACK TEST USING A VLC WIRELESS COMMUNICATION

Three types of high luminance LEDs with diameter 5 mm, 8 mm, and 10 mm were assessed. The data transmission characteristics of the three types of high luminance LEDs were tested before they were irradiated. After gamma ray irradiation experiments, their LED blobs were colored. Using the same LED driving circuit and VLC receiving circuit, and their transmission errors were counted. Their transmission distances were assessed. Figure 10 shows BER (bit error rate) test method using data packet. The sine wave (sinusoidal) value is transformed into a VLC TX data packet (33 bytes). The VLC TX data packet is transmitted into air via LED drive circuits. If VLC RX data (sine wave value) are different from the VLC TX data in the RS-232C loopback test, data error is counted, as shown in Fig. 10. The transmission error occurs. Transmission errors mean that received data does not coincide with transmitted data including VLC line errors and VLC frame errors. In Fig. 10, SOF means start of (data packet) frame. EOF means end of frame. According to the results, the high luminance LEDs of which the bulbs were colored due to high dose gamma irradiation, had better transmission characteristics compared to the high luminance LEDs before gamma irradiation. The transmission distances were improved even when the issue of alignment on the optic axis between the LED and the PD was considered. In the case of a high luminance power LED, a separate driving circuit was made to conduct the experiment because of the high driving current and high junction temperature while using the same

VLC receiving circuit. The results are shown in Table 1.

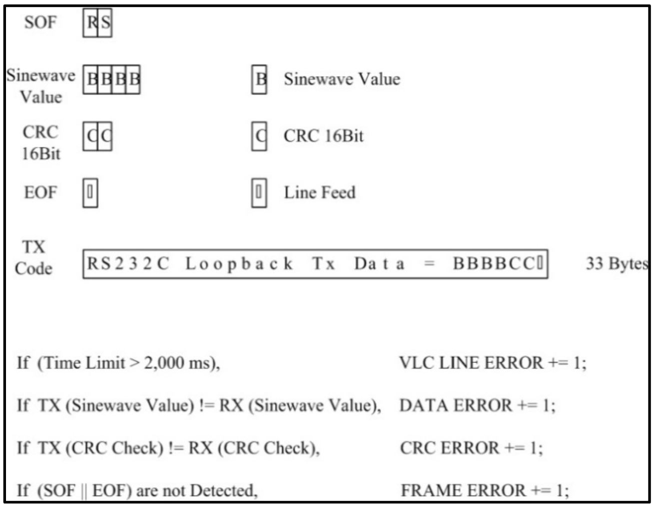

FIG. 10 DATA PACKET ARCHITECTURE USED IN THE RS-232C LOOPBACK TEST USING A VLC WIRELESS COMMUNICATION

TABLE 1 VLC DATA TRANSMISSION OF HIGH LUMINANCE LEDS

LED Diameter (Color)	Transmission Distance	
	Before Gamma Ray Irradiation	After Gamma Ray Irradiation
5mm(White)	320mm	410mm
8mm(White)	280mm	270mm
10mm(Red)	450mm	570mm
12mm(White/Power LED)	≥ 1,000 mm	≥ 1,000 mm

These results indicate that the coloring (brown) of the high luminance bulb moved the light emitting wavelength of the high luminance LED to the wavelength range in which the light receiving sensitivity (quantum efficiency) of the PD was high. The transmission distance seemed improved because the quantum efficiency of the PD was higher in the red-infrared wavelength region compared to other visible light wavelength ranges. To identify the improvement in transmission distance characteristics of high luminance LEDs after high dose gamma ray irradiation, the light emitting pattern of the LEDs was observed using a CCD camera. The results are presented in Table 2, Figure 11 and 12, indicating that the beam characteristics (light emitting pattern) of high luminance LEDs were improved after gamma ray irradiation. Figure 11 shows images that were histogram equalized to improve the observation performance of the original images. In the case of a high luminance red LED, which is 10 mm in diameter, the light emitting pattern formed a two-ring shaped structure prior to gamma ray irradiation. After the irradiation of a high dose gamma ray amounting to 288 kGy, the light emitting pattern of the beam changed from a two-ring shaped structure to a one-ring shaped structure because of the coloring effect of the LED bulb and the degree of focusing of the beam.

TABLE 2 MEASUREMENT OF LIGHTING PATTERN OF HIGH LUMINANCE LED

LED	Before Gamma Ray Irradiation			After Gamma Ray Irradiation		
	Drive Current	F #	Beam pattern	Drive Current	F #	Beam pattern
5 mm (White)	50 mA	F8	circle	52 mA	F11	circle
10 mm(Red)	62 mA	F8	2 circles	62 mA	F8	circle
F #: aperture (9mm/f1.4) of CCD camera lens						

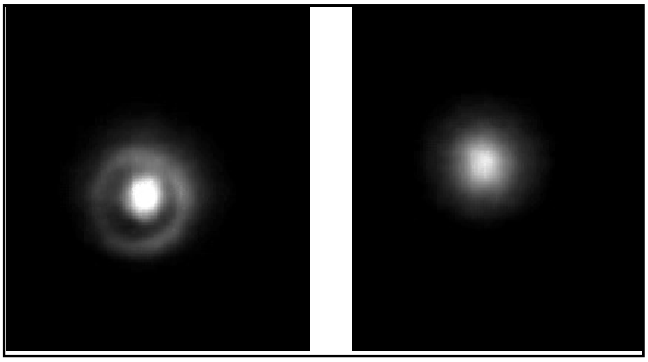

FIG. 11 LIGHTING PATTERNS OF HIGH LUMINANCE RED LED BEFORE AND AFTER HIGH DOSE-RATE GAMMA RAY IRRADIATION (LEFT: BEFORE, RIGHT: AFTER GAMMA DOSE)

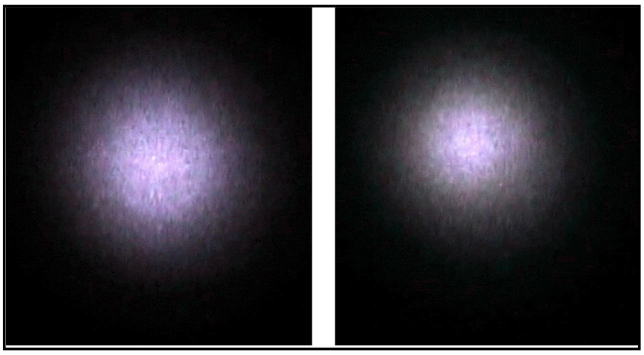

FIG. 12 LIGHTING PATTERNS OF HIGH LUMINANCE WHITE LED BEFORE AND AFTER HIGH DOSE-RATE GAMMA RAY IRRADIATION (LEFT: BEFORE, RIGHT: AFTER GAMMA DOSE, F11)

In the case of the 5-mm diameter white LED, shown in Figure 12, the beam pattern observed at f8 before gamma irradiation was similar to that observed at f11 after high dose gamma ray irradiation. This occurred because of the effect of coloring of the LED bulb resulting from the irradiation, which improved the focusing of the light emitting beam pattern. Therefore, the intensity of the beam per unit area received by the PD increased, and the transmission distance improved accordingly.

Design of a Module for Visible Light Communication

To apply a sensor communication network using visible light wireless communication inside a reactor building, biological radiation shield walls should be utilized. The minimum airline distance between

biological radiation shield (bio-shield) walls is 3.5 m, and maximum beeline distance is about 10 m, shown in Fig. 13. For example, to transmit data of the RTD sensor which is installed at the reactor coolant pipe connected between reactor pressure vessel and stream generator, to the nearby bio-shield wall using visible light, at least 3.5 m-length airline distance is required. In this paper, assuming that data of the RTD sensor is transmitted to the bio-shield wall using RS-232C interface, a RS-232C visible light wireless transmission link was designed and fabricated. Figure 14 shows a module of visible light wireless transmission link.

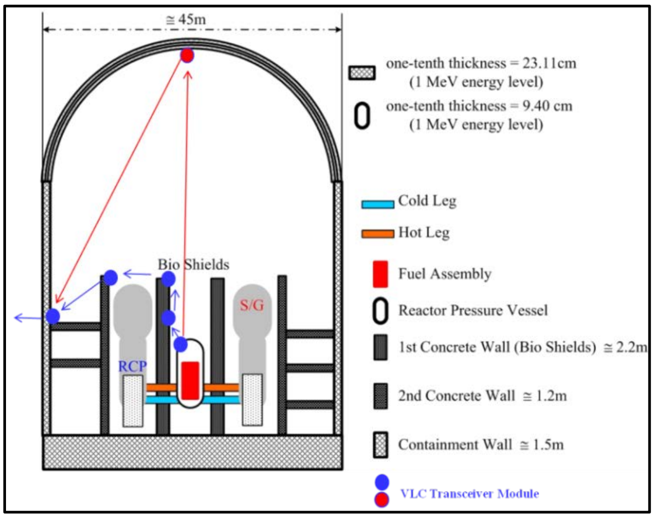

FIG. 13 A VLC WIRELESS DATA TRANSMISSION CONCEPT DIAGRAM USING BIO-SHIELDS INSIDE THE REACTOR CONTAINMENT BUILDING OF THE NUCLEAR POWER PLANT

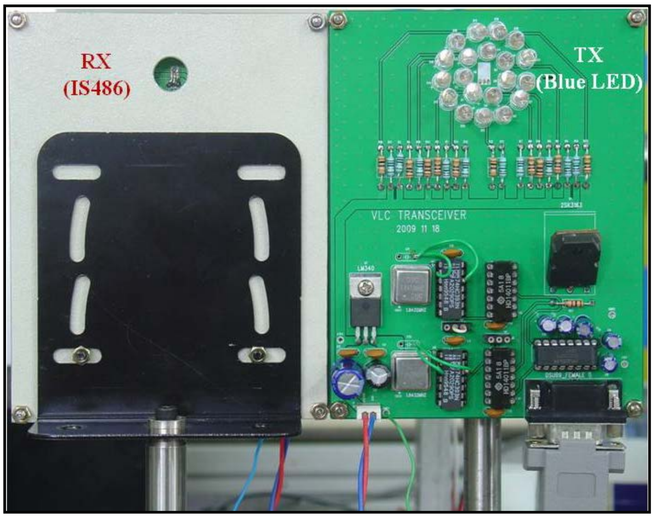

FIG. 14 VLC TRANSCEIVER MODULE (LEFT: PHOTO DETECTOR FOR RX IN THE BACKSIDE, RIGHT: LEDS FOR TX IN THE FRONT FACE)

Photo detector of a VLC transceiver module is IS486, embedded with preamplifier. The IS486 (photo detector) converts receiving light signal to TTL signal. Figure 15 shows the luminance of VLC transceiver (TX module) measured by a lux meter (LX-102). After a gamma ray irradiation (4kGy/h x 72 hours), the threshold voltage the LED did not changed, but the luminous efficiency of the LED was reduced slightly.

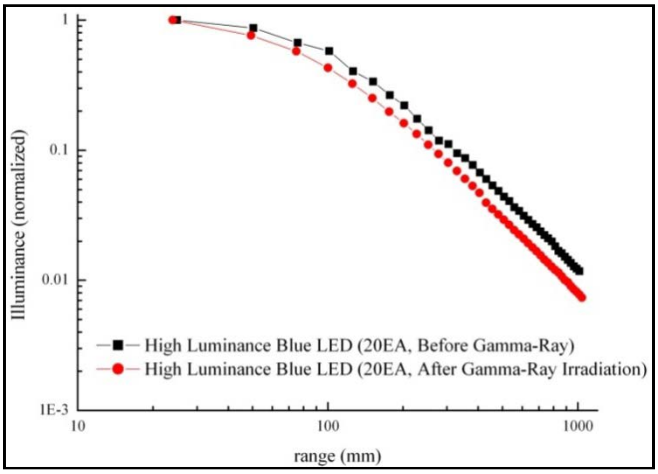

FIG. 15 LUMINANCE INTENSITY OF HIGH LUMINANCE BLUE LED

To verify airline distance for in-containment sensor network application, VLC wireless data transmission experiments using LED array module were composed of 20 blue LEDs. For the data transmission range measurement, a RS-232C loopback test was executed as shown in Figure 16 and Figure 17. And the results are shown in Table III.

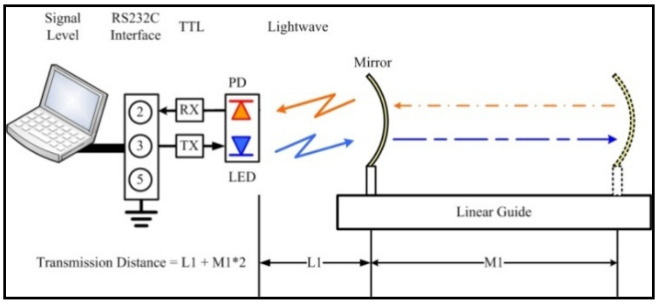

FIG. 16 BLOCK DIAGRAM OF RS-232C LOOPBACK TEST

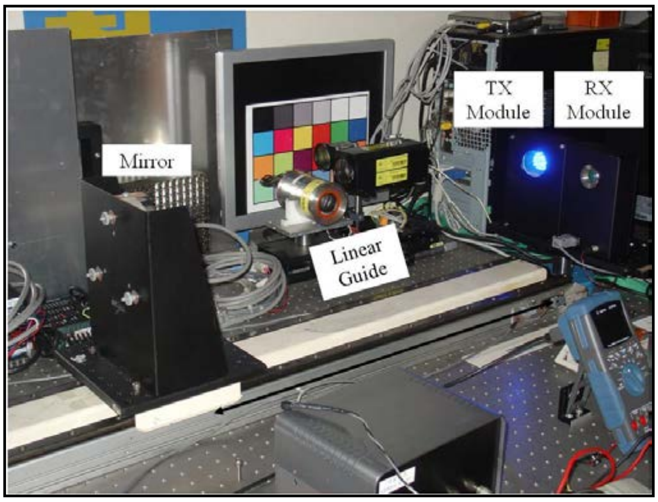

FIG. 17 AN EXPERIMENTAL SETUP FOR A RS-232C LOOPBACK TEST

TABLE 3 VLC DATA TRANSMISSION LENGTH OF BLUE LED ARRAY MODULE

Data Rate	Before Gamma Ray Irradiation		After Gamma Ray Irradiation (288 kGy TID)	
	Distance	Value of Lux Meter	Distance	Value of Lux Meter
19.2 kbps	146 cm	5.481 mV	158 cm	4.931 mV
38.4 kbps	146 cm	5.481 mV	155 cm	5.002 mV
57.6 kbps	142 cm	5.589 mV	150 cm	5.175 mV
115.2 kbps	136 cm	5.814 mV	144 cm	5.383 mV

Lighting intensity attenuation curve was modelled using the luminance data as shown in Fig. 16.

$$I_R = I_0 R^{\alpha} \quad (1)$$

In formula (1), R is range, and α means attenuation coefficient. I_0 means instantaneous beam intensity of a LED array source. From the modelled result, we estimated attenuation coefficient and calculated the number of LEDs, required for the VLC wireless data link at the condition of the 3.5 m minimum airline distance between RTD sensor and bio-shield wall. The results are shown in Table IV.

TABLE 4 THE NUMBERS OF BLUE LEDS, REQUIRED FOR VLC WIRELESS DATA LINK AT THE MINIMUM 3.5M DISTANCE

Data Rate	Before Gamma Ray Irradiation	After Gamma Ray Irradiation (288 kGy TID)
57.6 kbps	50 EA	39 EA

Conclusions

To apply visible light wireless communication systems as sensor/communication network systems for monitoring and controlling safety systems in nuclear reactor buildings, gamma rays were irradiated at a dose rate of 4kGy/h, corresponding to the DBA requirement on high luminance LEDs which are core elements of visible light wireless communication. Using this process, visible light wireless data transmission experiments were conducted and transmission distances were measured. According to the results, the transmission distance of high luminance LEDs whose bulbs were colored due to the high dose gamma ray irradiation, increased compared to the LEDs before gamma ray irradiation. Given this result, it is considered that the coloring of the LED bulb, due to exposure to high dose gamma rays, moved the light emitting wavelength to the wavelength range of the PD with high light receiving sensitivity, indicating that the VLC wireless data transmission distance increased. The light emitting pattern of high luminance LEDs after high dose gamma ray irradiation was observed using a CCD camera. According to the results, the width of the light emitting beam decreased because of the effects of LED bulb coloring resulting from high dose gamma irradiation, which increased the intensity of the beam per unit area received by the PD so that the transmission distance improved accordingly. If the Si-CMOS FPGA and ASIC chip set, functioned as the sensor communication network protocol driver, are effectively shielded by lead material, the VLC wireless communication technology can be applicable to in-containment building as an ad-hoc sensor network of nuclear power plant.

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Young Soo Choi was born in Daegu, Korea in 1966. He received the B.E. and M.E. degrees in electronic engineering from Kyung Pook National University, Daegu, Korea, in 1991 and 1993 respectively. He received Ph. D. degree in electronic engineering from Chung Book National University, Cheongju, Korea in 2010, Since 1995, he has been with the Nuclear Convergence Division, Korea Atomic Energy Research Institute, where he is now a principal researcher. His research interests are in robot visions for nuclear emergency response robot system, underwater robot system for the inside inspection of the hot leg & cold leg pipe in the RCPB (reactor coolant pressure boundary) area, VLC (visible light communication), and radiation-hardened vision systems for the nuclear power plant.

Seok Boong Hong was born in Seoul, Korea in 1957. He received the B.E., M.E. and Ph. D. degrees in electronic engineering from Sung Kyun Kwan University, Seoul, Korea, in 1979, 1982 and 2002 respectively. Since 1983, he has been with the Nuclear Instrumentation & Control Division, Korea Atomic Energy Research Institute, where he is now a principal researcher. His research interests are in radiation monitoring system for nuclear research reactor, nuclear instrumentation system, and radiation-sensitive detection systems for the nuclear power plant.